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Chemical Structure, Quality Indices and Bioactivity of Essential Oil Constituents

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Additional information is available at the end of the chapter

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Abstract

Essential oil (EO) is a mixture of low molecular weight constituents that are responsible for its characteristic aroma. These constituents include terpenoid and non-terpenoid hydrocarbons and their oxygenated derivatives. This chapter focuses on the heterogeneous composition of the essential oils. It discusses the usage of essential oil constituents as a key marker of the oil quality, freshness and unique characteristics. It describes the biological activity and synergistic effect of the essential oil constituents as antioxidant, antibacterial, antifungal and anticancer agents.

Keywords: chemical structure, quality characteristics, bioactivity, antioxidant, antimicrobial, antitumor

1. Introduction

Essential oil (EO) is defined as odorous product, of complex composition, obtained from part of plant or whole plants through various methods. It has the characteristic taste and odor of the plant from which it was derived [1, 2]. This variation in composition could be due to a variety of plants [3], geographical locations [3, 4], harvesting seasons [5–7], drying methods [8] and extraction methods [9, 10].

The quality, freshness and uniqueness of an essential oil are major considerations pertaining to its value [11]. Essential oils are highly sensitive to heat, moisture and oxygen [12]. Formation of oxygenated terpenes, chemical transformations, or polymerization are features of aging

processes that led to quality loss. Therefore, quality control of essential oils needs to be monitored by producers, traders, or essential oil manufacturers [13, 14].

Essential oils have wide variety of bioactivities and play an important role as ideal natural sources of antimicrobial, antioxidant and chemopreventive agents [15–17]. They have potential therapeutic applications in the prevention of cancer [18].

2. Chemical composition of essential oil

Essential oils (EOs) are volatile constituents obtained from aromatic plant material, including leaves, rhizomes, flowers, roots, bark, seeds, peel, fruits, wood and whole plants [19]. A few of the essential oils are found in animal sources, for example, musk and sperm whale, or are produced by microorganisms [20]. In plants, essential oils occur in oil cells, secretory ducts or cavities, or in glandular hairs. Essential oils can be isolated by steam distillation from an aromatic plant because of their volatility [21]. Different constituents in EOs exhibit varying smell or flavor [9]. The perception of individual volatile compounds depends on their threshold [22].

Essential oils are a complex mixture of polar and non-polar compounds [23]. The essential oil composition depends on the species of the extracted plant, the geographic location of this plant, harvest time and extraction technique [24].

EOs can be classified into the four main groups: [25, 26]

1. Terpenes, related to isoprene
2. Straight-chain compounds not containing any side chain
3. Phenylpropanoids (benzene derivatives)
4. Miscellaneous group having varied structures not included in first three groups (sulfur- or nitrogen-containing compounds)

2.1. Terpenes, related to isoprene or isopentene

Essential oils constituents can be divided into two major groups: terpene hydrocarbons and oxygenated compounds [27].

2.1.1. Terpene hydrocarbons

Terpenes are the most common class of chemical compounds found in essential oils [28]. Terpenes are synthesized in the cytoplasm of plant cells, through the mevalonic acid pathway [19]. Terpenes have been regarded as polymers of isoprene (C_5H_8) joined in a repetitive head-to-tail manner [29] as shown in **Figure 1**.

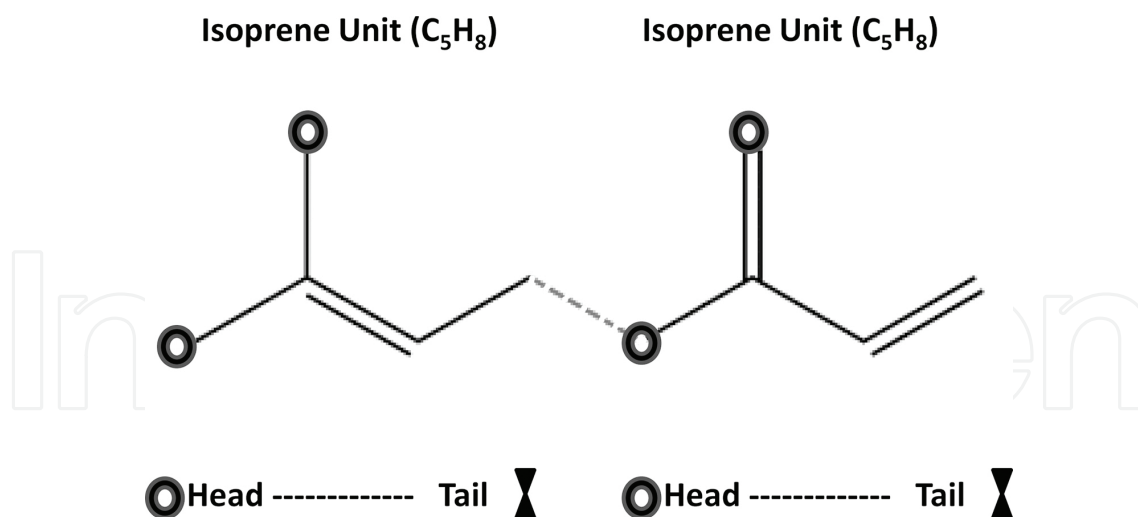


Figure 1. Link of isoprene molecules.

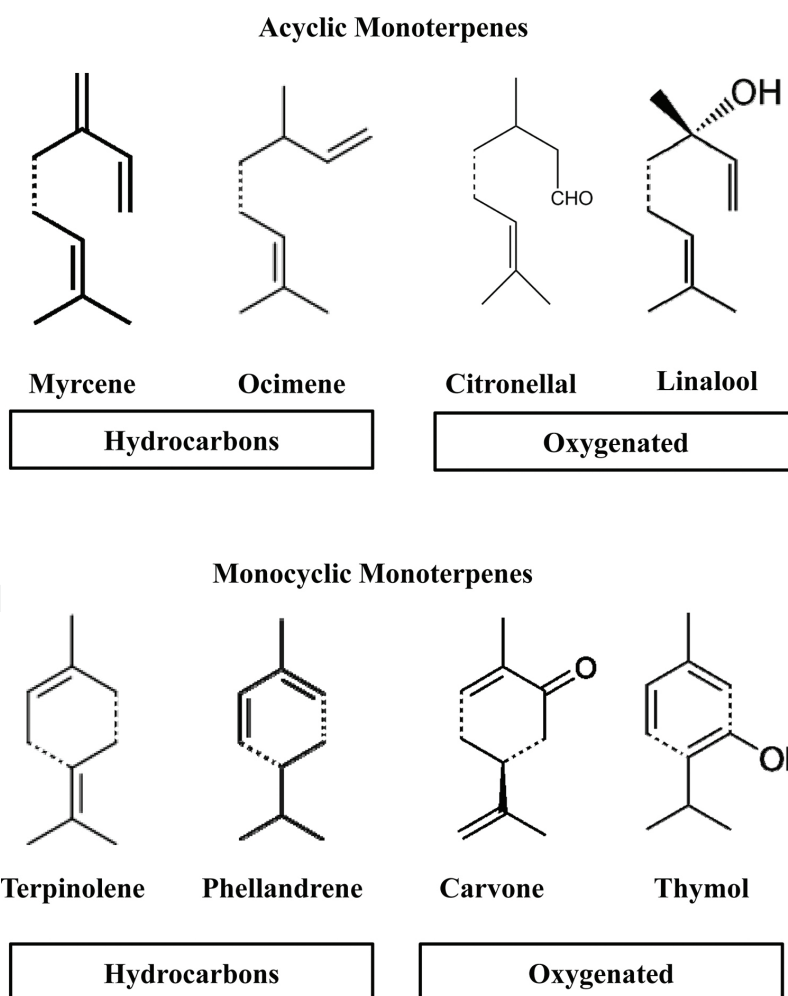


Figure 2. Chemical structures of acyclic and monocyclic monoterpenes.

They could be classified according to the fusion of the isoprene units or to the number of the rings [28]. Terpenes can be classified into hemiterpenes (1 unit), monoterpenes (2 units), sesquiterpenes (3 units), diterpenes (4 units), sesterterpenes (5 units), triterpenes (6 units) and polyterpenes (many units) [30]. The combinations of two isoprene units are called a “terpene unit.” Monoterpenes ($C_{10}H_{16}$) are formed by the attachment of two isoprene units (at least one double bond). These terpenes have a hydrocarbon skeleton which can be rearranged into acyclic, cyclic, or aromatic (**Figure 2**). Cyclic monoterpenes can be classified according to their ring size such as monocyclic monoterpenes, bicyclic monoterpenes and tricyclic monoterpenes [31] **Figure 3**. These compounds oxidize easily because of their rapid reaction to air and heat sources [32].

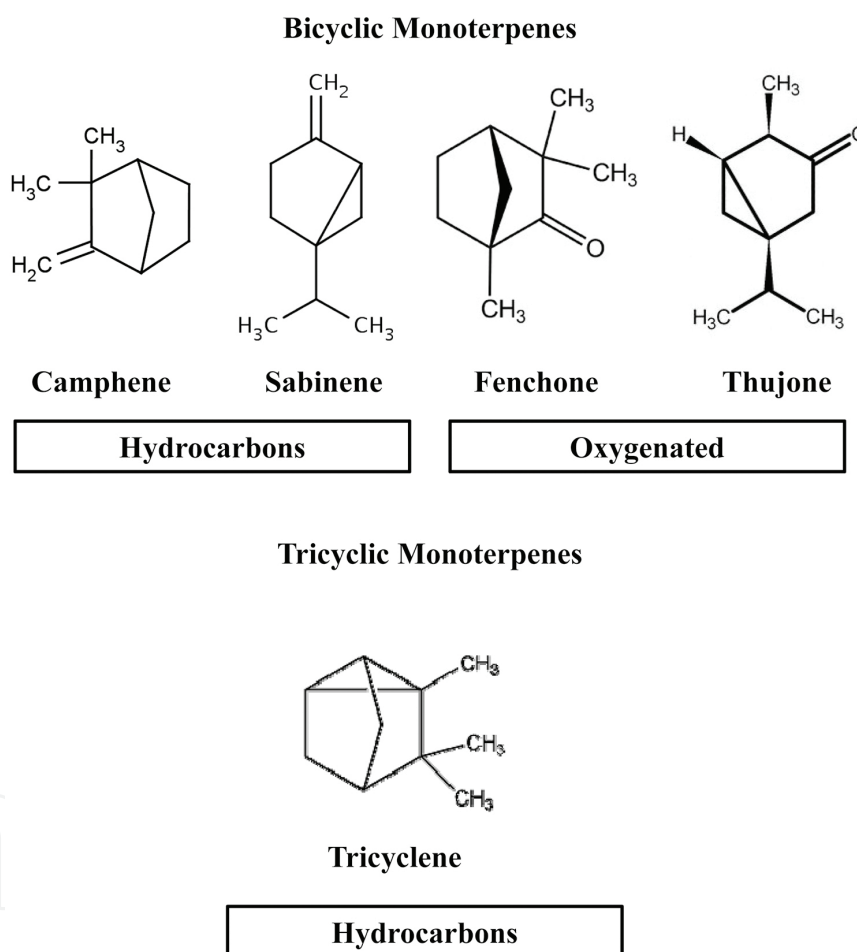


Figure 3. Chemical structures of bicyclic and tricyclic monoterpenes.

Sesquiterpenes ($C_{15}H_{24}$) are the second to the dominant monoterpenes. They are formed from the combination of three isoprene units [29]. Sesquiterpenes are unsaturated compounds. There are linear, branched, or cyclic sesquiterpenes (**Figure 4**). Sesquiterpenes are unsaturated compounds. Cyclic sesquiterpenes can be classified into monocyclic, bicyclic, or tricyclic [31] (**Figure 5**). Diterpenes are formed by the head-to-tail combinations of four isoprene units followed by rearrangement and/or substitutions (**Figure 6**).

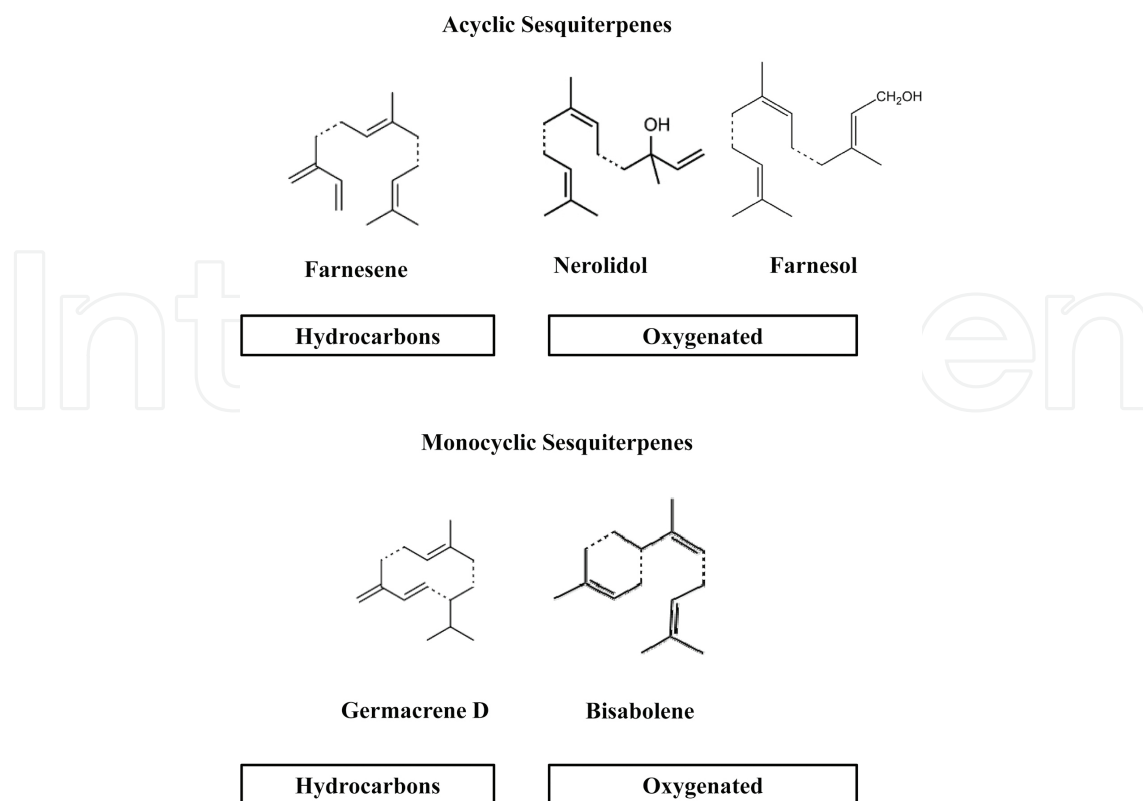


Figure 4. Chemical structures of acyclic and monocyclic sesquiterpenes.

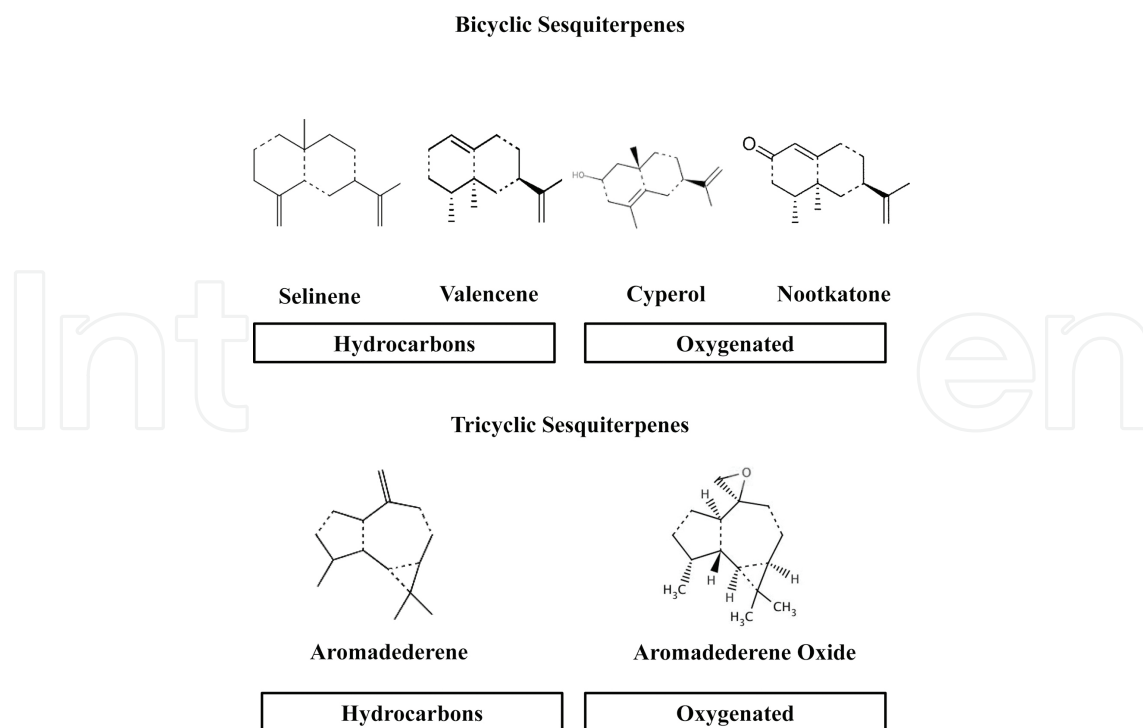


Figure 5. Chemical structures of bicyclic and tricyclic sesquiterpenes.

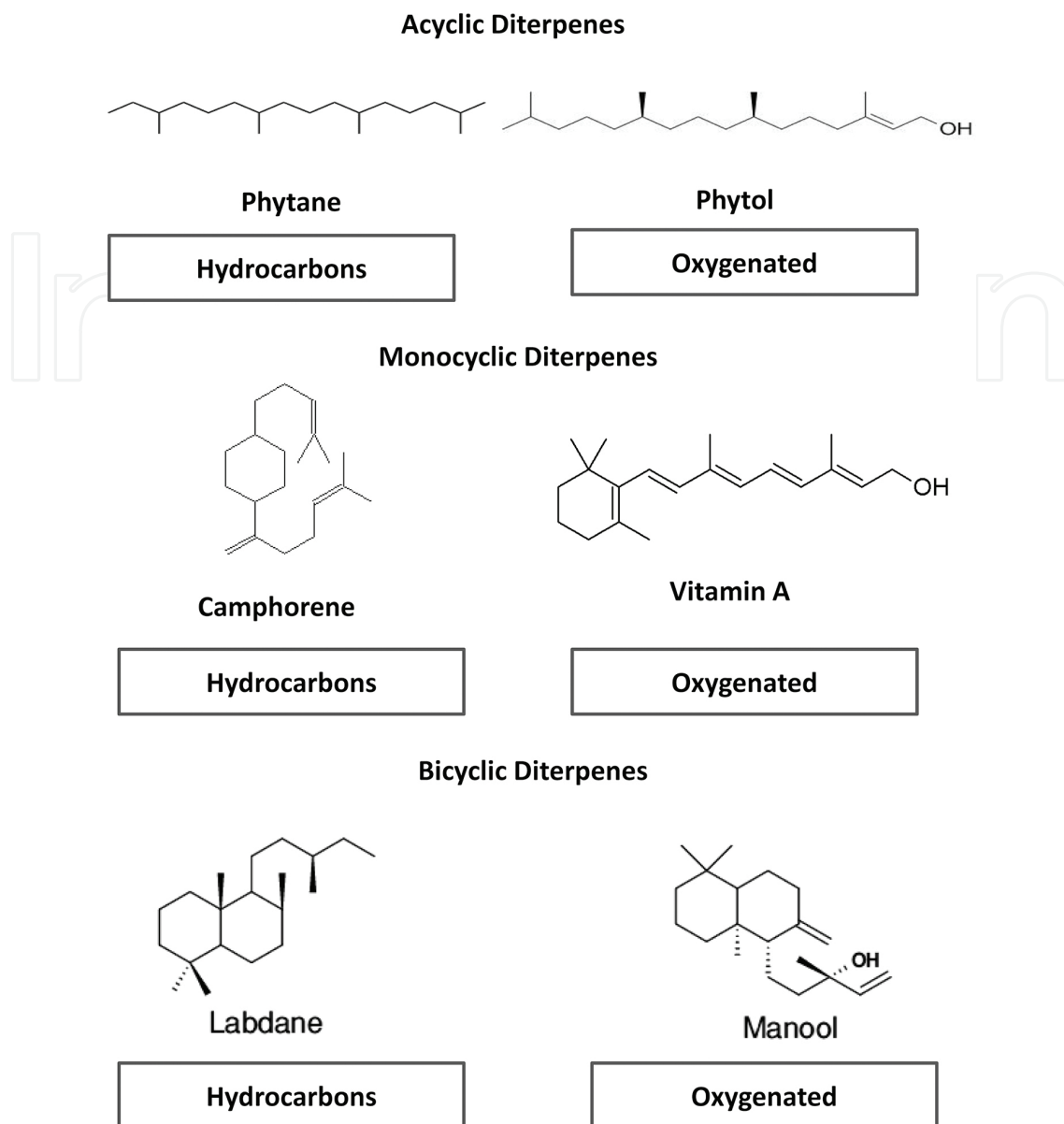


Figure 6. Chemical structures of acyclic, monocyclic and bicyclic diterpenes.

They are important components of plant resins [33]. Diterpenes, triterpenes and tetraterpenes are present at a very low concentration in essential oils [27, 34]. Their recovery increases with increasing steam distillation times [35] and influenced by the extraction method.

2.1.2. Oxygenated compounds (terpenoids)

The oxygenated compounds are highly odoriferous [36]. Terpenoids are volatile secondary metabolites which give plants their fragrance [37]. Terpenoids can be subdivided into aldehydes, ethers, alcohols, esters, ketones, phenols and epoxides [19]. Examples: (+)-Borneol occurs in camphor, rosemary and lavender oils. It has a camphor-like odor, with a slightly peppery note [38]. Carvacrol is found in oregano and thyme [39] oils. It has a herbaceous,

phenolic odor [32]. (-)-Carvone has a herbal scent and is found in caraway seed oil; (+)-carvone with a spicy-minty odor can be found in spearmint oil [40]. 1,8-Cineole is obtained primarily by isolation from eucalyptus oil. It has a camphor odor [41].

2.2. Straight-chain compounds, not containing any side branches

This group contains only straight chain non-terpenoid hydrocarbons and their oxygen derivatives: alcohols, aldehydes, ketones, acids, ethers and esters. These hydrocarbons range from n-heptane, to compounds with 35 carbon atoms. Heptane content represented 3.8 and 36.8% of the wood volatile oils of *Pinus jeffreyi* and *Pinus sabiniana*, respectively [42]. The leaf alcohol (3(Z)-hexen-1-ol, **Figure 7**) and its esters are responsible for the intense grassy-green odor of freshly cut green grass and leaves via the octadecenoic pathway [43–45].



Figure 7. Chemical structure of leaf alcohol.

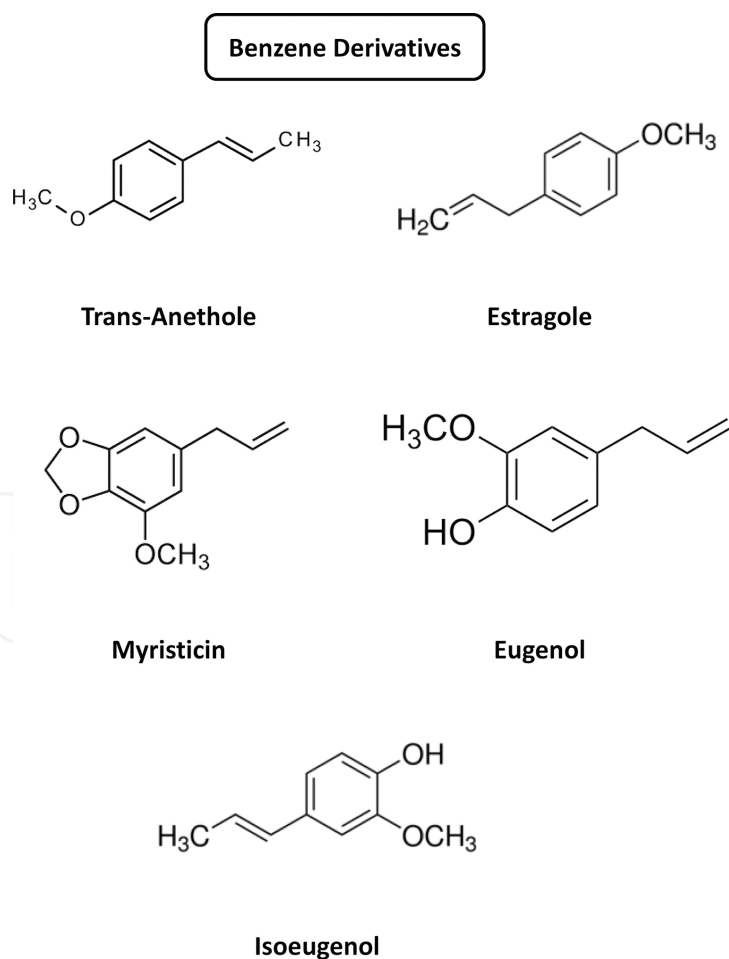


Figure 8. Chemical structures of phenylpropenes.

2.3. Phenylpropenes (benzene derivatives)

These aromatic compounds are an important group to flavor and fragrance industry though it constitutes a relatively small part of the essential oils. This non-terpenoid group comprises of constituents derived from n-propyl benzene. The aromatic ring may carry hydroxy, methoxy and methylene dioxy groups; the propyl side chain may contain hydroxyl or carboxyl group [25].

Phenylpropenes constitute a subfamily of phenylpropanoids that are synthesized from the amino acid phenylalanine and L-tyrosine via the shikimic acid pathway [46]. Examples of this group include trans-anethole, methyl chavicol, eugenol, isoeugenol, vanillin, safrole, myristicin and cinnamaldehyde [19, 47] (Figure 8).

2.4. Miscellaneous group (sulfur- and nitrogen-containing compounds)

The representatives of this group are the compounds, which are not included in the above mentioned three groups [25]. They are different degradation products originating from unsaturated fatty acids, lactones, terpenes, glycosides and sulfur- and nitrogen-containing compounds [48].

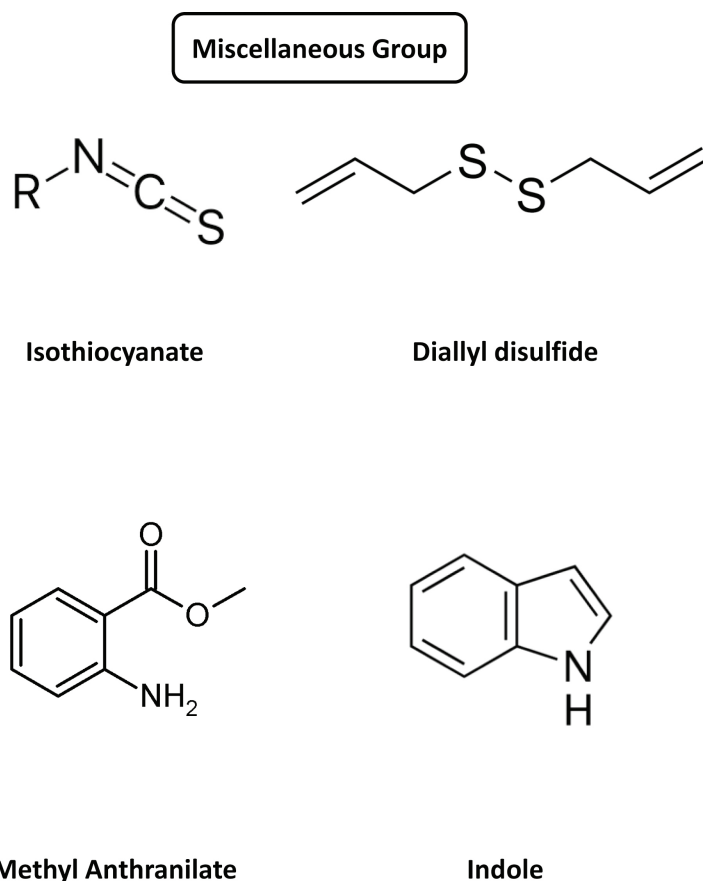


Figure 9. Chemical structures of sulfur- and nitrogen-containing compounds.

Sulfur- and nitrogen-containing compounds occur mainly as aglycones or glucosinolates, or their breakdown products, which include isothiocyanates [49]. The Brassicaceae is an important source of glucosinolates and isothiocyanates [50]. Garlic, onion, leek and shallots contain volatile sulfur compounds, namely allyl sulfide, dimethyl sulfide, diallyl disulfide and dimethylthiophene [51]. The sulfur compounds are responsible for the characteristic aroma and taste [52]. Cysteine sulfoxides including alliin predominate in mature, intact *Allium* spp., along with γ -glutamylcysteines [53]. Upon rupture, such as when chopped or pressed, the action of a class of enzymes known as alliinases catalyzes the conversion of cysteine sulfoxides into the volatile thiosulfinates [54] including allicin. Allicin makes up 70–80% of the thiosulfinates. Allicin and other thiosulfinates decompose diallyl sulfide, diallyl disulfide, diallyl trisulfide, dithiins and ajoene, while the γ -glutamylcysteines are converted to S-allyl cysteine through a non-alliin/allicin pathway [53]. Nitrogen-containing compounds are found in only a few essential oils. Examples include methyl anthranilate, indole, pyridine and pyrazine. Methyl anthranilate is present in orange, lemon and bergamot oils [35] and jasmine oil [55]. Indole occurs in neroli and some citrus fruit oils [32]. Pyridines and pyrazines occur in black pepper, sweet orange and vetiver oils [35] (Figure 9).

3. Quality indices of essential oils

The studies have shown that a differentiation in oil quality and volatile components is associated with climatic conditions, geographical location of collection sites and other ecological and genetic factors. The influence of those factors on the accumulation of distinct volatile compounds defines its chemotypes [56–58].

3.1. Black pepper oil

Black pepper oil is obtained from the dried unripe fruits of *Piper nigrum* [59]. The monoterpenes hydrocarbons (i.e., limonene, sabinene, β -pinene, 3-carene and phellandrene) to sesquiterpenes hydrocarbons (β -caryophyllene) ratio represents the quality of the oil and indicates the aroma value; the monoterpenes provide the body of the flavor, but the sesquiterpenes provide the spicy note. A lower value represents a higher quality of the essential oil [60, 61]. A high total monoterpenes content results in a strong “peppery” top-note and a predominantly pinene content of the terpene fraction gives a turpentine-like note, while a high caryophyllene content results in a sweet, flowery note, which is more desirable in the flavor industry [62]. In addition to the ratio of monoterpenes to sesquiterpenes, the oxygenated compounds are supposed to provide the heart of the aroma of pepper oil [63]. The pepper oil extracted with supercritical fluid carbon dioxide was found to have a higher content of caryophyllene and oxygenated sesquiterpene compounds. The volatile oil obtained under these conditions was considered superior to the steam-distilled oil, using aroma, taste and monoterpene to sesquiterpene hydrocarbons ratio as the criteria [64, 65]. Tipsrisukond et al. [66] reported that this ratio reached 3.02 and 0.95 in the steam distilled oil and supercritical fluid extract, respectively. On the other hand, this ratio was found to be 2.21 in the hydro-distilled oil while it was 1.66 in the supercritical fluid extract [67].

Storage of black pepper hammer milled powder for 6 months at 4°C, markedly increased monoterpene to sesquiterpene hydrocarbons ratio from 1.31 to 4.47. They attributed this increase to the degradation of some sesquiterpenes, as a result of oxidative decomposition during storage [68].

3.2. Cardamom oil

Cardamom oil is obtained from the dried ripe fruits of *Elettaria cardamomum* [59]. Salzer [60] reported that 1,8-cineole and α -terpinyl acetate together with the terpene alcohols are important for the evaluation of the aroma quality of cardamom. 1,8-Cineole is reported to contribute to pungency while terpinyl acetate is known for its desirable, pleasant flavor of cardamom [69, 70]. The higher level of α -terpinyl acetate compared to that of 1,8-cineole could be used as an indicator of the superior quality of cardamom essential oil [71, 72].

Monoterpenes hydrocarbons are less odoriferous than oxygenated monoterpenes [73]. Amma et al. [74] recorded superior flavor quality for the Malabar variety with the highest α -terpinyl acetate/1,8-cineole ratio (1.55) when compared with the Mysore variety (1.34). Morsy [75] found that this ratio exceeded 1.6 when ultrasound-assisted extraction (30 W, for 30 min) was used as a pretreatment for hydrodistillation (30 min) compared to 1.13 when hydrodistillation was conducted for 6 h. The presence of a low level of hydrocarbons in cardamom oil could be used as an indicator of its high quality [74].

3.3. Caraway essential oil

Caraway oil is obtained from the dried ripe fruits of *Carum carvi* [59]. The main components of caraway essential oil are carvone and limonene, whose mixture constituted from 97.69 to 98.62% of total oil composition [76]. The overall quality of fruits is considered to correlate with the content of essential oil and its carvone/limonene (C/L) ratio: the higher the ratio, the better the quality. C/L ratio varies from 0.90 to 2.74 [77, 78]. This ratio is variable during ripening. Limonene is of high level in green immature seeds [79]. Aćimović et al. [76] considered the quality of essential oil poor when C/L ratio recorded 0.47. The essential oil of biennial caraway varieties usually has a higher C/L ratio compared to that of the annual varieties [80, 81]. The C/L ratio decreased with the time of storage (70 days, at room temperature) of caraway seed samples [82].

3.4. Peppermint oil

Peppermint (*Mentha piperita*) has bright green leaves, with a fresh, slightly sweet, tangy, peppery and strong menthol notes [83]. The principal constituents of peppermint oil are menthol (30–55%), menthone, menthyl acetate and other esters [84]. The ratio of menthol/menthone is the major determinant of the flavoring quality of distilled essential oil [85]. For commercial purposes, a high oil yield with a ratio of menthol to menthone of 2:1 is desired [86]. In general, high-quality peppermint oil (i.e., high menthol/menthone ratio) develops during full bloom [87]. The English oil contains 60–70% of menthol, the Japanese oil con-

tains 85% and the American only about 50%. The odor and taste afford a good indication of the quality of the oil.

3.5. Lavender oil

Lavender flowers (*Lavendula angustifolia*) have a strong perfumery odor with crusty woody undertones a camphor-like note. The leaves have herbaceous and more pronounced bitter notes [83]. Linalool and its ester form, linalyl acetate, are the most abundant monoterpenes in lavender varieties and are the most desired components of the lavender oil, while trace amounts of camphor generally contribute an undesirable odor, diminishing the quality of the oil [88–90]. The linalyl acetate to linalool ratio may change in different distillation times and may affect the final odor of the oil [91]. The oil samples that were obtained after 1 and 2 h of steam distillation had linalyl acetate to linalool ratio of 0.57 and 0.44, respectively. The ratio of linalyl acetate to linalool should be higher than one in high-quality lavender oil [92].

3.6. Rose oil

Rosa damascena is an ornamental plant. This plant is used for food flavoring as dried flowers, dried bud and dried petals [93]. The flavor compounds that contribute to the distinctive scent of rose oil are β -damascenone, β -damascone, β -ionone and rose oxide. Even though these compounds exist in <1% of rose oil, they make up for more than 90% of the odor content due to their low odor thresholds. The concentration of β -damascenone is considered as the marker for the quality of the rose oil [94, 95].

Citronellol/geraniol (C/G) ratio could be used for evaluating the quality of rose oil [96]. The finest quality rose oil has C/G ratio between 1.25 and 1.30 [97]. In the rose oil trade, the citronellol content should be higher than 35%. The oils from non-fermented petals generally contain citronellol lower than this level. Therefore, a short-term fermentation is conducted to increase the citronellol content. The C/G ratios were higher in the oils distilled from long-term fermented petals (e.g., 10.3 in 36 h fermentation) than non-fermented petals (0.56). Based on these results, rose oils distilled from long-term fermented petals are of poor quality [98].

3.7. Ginger oil

Ginger oil is obtained from the rhizomes of *Zingiber officinale* [59]. α -Zingiberene is the major sesquiterpene hydrocarbon of ginger oil [99]. Salzer [60] reported that citral, zingiberene, β -sesquiphellandrene and ar-curcumene could be used for evaluating the quality of the ginger oil. Govindarajan [100] reported that citral and citronellyl acetate are co-determinants of the odor of ginger oil, while zingiberene and β -sesquiphellandrene are the main components of the freshly prepared oil. ar-Curcumene increased with storage. A good quality oil has a ratio of zingiberene + β -sesquiphellandrene to ar-curcumene = 2:3.

The lemony note is attributed to citral together with α -terpineol, while nerolidol is responsible for the woody note. β -Sesquiphellandrene and ar-curcumene contribute to the characteristic ginger flavor [101].

3.8. Juniper oil

Juniper (*Juniperus communis*) has green and sharp leaves (needles) [102]. Juniper's odor is woody and astringent with sweet, lemon and pinelike overtones. It has a ginlike aroma. Its flavor is released when it is lightly crushed [83].

Butkienė et al. [103] identified 143 components in the juniper leaves essential oil. They found that monoterpenes (M)/sesquiterpenes (S) ratio ranged from 2:1 to 5:1 according to localities in Vilnius district, Lithuania. Sela et al. [104] found that M/S ratio ranged from 1:1 to 3:1 for leaves essential oil of Macedonian juniper, from different localities. Orav et al. [105] reported that M/S ratio of juniper berries oils was higher (4:1) than that obtained from leaves samples (2.5:1). Pourmortazavi et al. [106] found that supercritical fluid extraction products from *J. communis* L. leaves using carbon dioxide were markedly different from the hydrodistilled oil. The hydrodistilled oil was characterized by a high concentration of β -phellanderene. The ratio of α -pinene to 3-carene in hydrodistilled oil was high (0.62) compared with that of the supercritical carbon dioxide extracts (0.04–0.065). Looman and Svendsen [107] reported that the average ratio of α -pinene:sabinene:limonene was generally 21:45:5 in the leaf essential oil of Norwegian mountain juniper (*Juniperus communis* L. var. *saxatilis* Pall).

3.9. Oregano, thyme and savory oils

Oregano, wild marjoram, *Origanum vulgare*, has dark green fresh leaves. Fresh oregano is available whole, chopped, or minced. The dried light green leaves are available whole, flaked, or ground [83]. The thyme plant, *Thymus vulgaris* L., is an evergreen herb that is used for its flavor [108]. Summer savory, *Satureja hortensis*, is often used as a culinary herb either as a fresh or dried herb [109].

In oregano essential oil, the total content of the thymol and carvacrol was the highest and amounted to 67.51%; in thyme essential oil, 47.47%; and in savory essential oil, 49.71%. The thymol and carvacrol types have sharp, warm and penetrating herbal (thyme type) odors, with woody, spicy and tobacco-like notes; thymol itself has a powerful, medicated and herbaceous odor while carvacrol itself has a tar-like odor [110]. The ratio of carvacrol to thymol in oregano, thyme and savory essential oils was 15:1, 1:19 and 1.8:1, respectively [111]. Oils containing predominantly thymol are generally considered of superior quality [112, 113].

3.10. Lemongrass oil

Lemongrass (*Cymbopogon* spp.) is a tall perennial C4 grass belonging to the family Poaceae (Gramineae), commonly known as the “sweet grass family” [114]. Lemongrass gives a refreshing lemon-lime-like taste with a tinge of mint and ginger. It has a citral odor with floral-like (rose) and a fresh, grassy aroma. Its flavor is found in the lower tender part of the stem. The root-end stalk gives the most flavor. The whole fresh stalk becomes aromatic when it is crushed or cut. The dried form has a very little aroma [83]. The quality of the lemongrass essential oil is measured by its citral content [115, 116]. Citral is a natural mixture of two monoterpene aldehydes, geranial (trans isomer) and neral (cis isomer). Supercritical fluid extraction was found to be a superior process than steam distillation, producing better quality

lemongrass oil containing 90% citral [117]. The leaves yield aromatic oil, containing 70–90% citral. *C. flexuosus* has higher citral content than *C. citratus* [118, 119].

4. Bioactivities of essential oil constituents

Essential oils from different plant parts exhibit different biological activities [120]. Biological activities of essential oils include antioxidant, antimicrobial, antiviral, anti-mutagenic and anticancer [34]. Essential oils are complex mixtures of terpenoids and phenylpropanoids compounds extracted by distillation or solvent extraction [121]. Overall activity cannot be attributed to only one of the major constituents [122]. The inactive compounds might influence resorption, the rate of reactions and biological activity of the active compounds. The combination of the major and minor constituents modifies the activity to exert significant synergistic or antagonistic effect [123].

4.1. Antioxidant activity

Antioxidants are substances that protect cells from being oxidized by free radicals. Reactive oxygen species (ROS) are highly reactive toxic molecules. ROS induced oxidative diseases such as ageing, arteriosclerosis, cancer, Alzheimer's disease and Parkinson's disease [124]. Living cells possess scavenging activity to diminish excess ROS that induced cellular injury. These mechanisms become inefficient, with ageing and under external stress. Therefore, dietary supplementation of natural and synthetic antioxidants is required [125]. Some synthetic antioxidants cause liver damage and have carcinogenic effects. Natural antioxidants are preferred to synthetic ones [126].

The essential oil of lemon balm, containing neral/citral, citronellal, menthone and isomenthone, showed strong antioxidant activity [127].

The essential oils with good radical-scavenging activity could be arranged in the following order, clove > cinnamon > nutmeg > basil > oregano > thyme [128].

Misharina and Samusenko [129] stored a mixture of lemon, coriander and clove buds essential oils (1:1:1) at room temperature in the light for 145 days. They found that the mixture of the three essential oils increased the stability of limonene and γ -terpinene significantly higher than in the individual essential oils and inhibited oxidation of hexanal efficiently. It was shown that terpene hydrocarbons break free-radical chain reactions, which is accompanied by their irreversible oxidation into inert compounds, such as *p*-cymene. Therefore, terpene hydrocarbons do not exhibit the properties of prooxidants.

Wei and Shibamoto [130] proposed that terpenes and terpenoids that contribute to the antioxidant activity of essential oils include α -terpinene, β -terpinene and β -terpinolene in tea tree; 1,8-cineole in water mint, menthone and isomenthone in peppermint; thymol, eugenol and linalool in black cumin, cinnamon bark and ginger; and thymol and eugenol in thyme and clove leaf.

Eugenol, the major constituent of clove essential oil, was found to have an inhibitory activity against lipid peroxidation by interfering with chain reactions of free radicals. The inhibitory activity of eugenol was about fivefold higher than that observed for alpha-tocopherol [131]. Thymol and carvacrol the main constituents of thyme oil are shown to act as strong antioxidants [132]. The antioxidant activity of caraway oil may be due to the presence of linalool, carvacrol, anethole and estragole [133]. Marjoram and clove essential oils exerted a powerful antioxidant activity in beef burger prepared with sunflower oil during storage at -18°C for 3 months. The addition of marjoram oil at 250 mg/kg kept thiobarbituric acid value of the beef burger samples after 3 months of storage at a level not significantly different from that of control samples stored frozen for 1 month [134]. Flavoring refined corn oil with thyme increased its oxidative stability (induction time) from 4.36 to 6.48 h [135]. Blending cold-pressed oregano (*Origanum vulgare*) oil with sunflower oil at 10 and 20% levels increased its induction time from 3 to 6 h and 8 h, respectively. Assiri et al. [136] attributed the superior antioxidant activity of sunflower oil blends to the high levels of phenolic compounds in oregano oil.

4.2. Antibacterial activity

Essential oils display broad-spectrum inhibitory activities against various bacterial pathogens [137]. Essential oil is easily permeable through the cell wall and cell membrane due to its lipophilic characteristic. Interaction of essential oil components with polysaccharides, fatty acids and phospholipids causes loss of membrane integrity, leakage of the cellular contents, interference in proton pump activity and leads to cell death [124, 138–140]. Other important mechanisms of action include denaturation of cellular proteins [9, 34, 141]. Carvone partitioned in the lipid membrane [142], while terpinen-4-ol inhibits cellular respiration and both damage cell membrane function as a permeable barrier [143]. Carvacrol and *p*-cymene accumulate in the lipid phase of the membrane by causing expansion of the phospholipids bilayer and increasing spaces through which ion leakage might occur [144].

Sage essential oil is rich in antimicrobial agents [145]. The single layer wall of *S. aureus* is highly sensitive to essential oils with a high content of *p*-cymene [34]. Cold-pressed oregano (*Origanum vulgare*) oil exhibited antimicrobial activity against *Staphylococcus aureus*, *Escherichia coli*, *Salmonella enteritidis*, and *Listeria monocytogenes* with minimum lethal concentrations ranging between 160 and 320 µg/mL. The antimicrobial activity of the oregano oil could be due to the presence of phenolic constituents and the differences in the permeability of cell wall of those bacteria [136]. Ghabraie et al. [146] found that essential oils of Red bergamot (Flower top) and Chinese cinnamon (bark) inhibited *Escherichia coli*, *Listeria monocytogenes*, *Staphylococcus aureus* and *Salmonella Typhimurium*. The inhibition zone ranged from 20 to more than 70 mm depending on the target bacteria. Chinese cinnamon inhibited *S. aureus* and *E. coli* at minimum inhibition concentration of 470 ppm in microbroth dilution assay. Antibacterial activity of Red bergamot oil could be due to carvacrol and *p*-cymene, while trans-cinnamaldehyde is responsible for this effect in Chinese cinnamon oil. Radaelli et al. [147] studied the antimicrobial activities of basil, rosemary, marjoram, peppermint, thyme and anise essential oils against *Clostridium perfringens* strain A. They found that all oils

showed bactericidal activity at their minimum inhibitory concentration, except anise oil, which displayed bacteriostatic effect.

4.3. Antifungal activity

Fungi are important causes of human infections [148]. Several crops are susceptible to fungal attack either in the field or during storage [149]. Fungicide residues are problems for the food industry [150]. Prevention of fungal growth is an effective way of impeding mycotoxin accumulation [151]. Essential oils have the ability to attack the life cycle of molds [152].

The high cost of essential oils production and the low concentration of active constituents limit their direct use in the control of fungal diseases of plants and animals. Therefore, investigation of antifungal compounds of the essential oils is considered important because of the possibility of synthesizing these compounds for the use in the control of fungal diseases [153].

Bouchra et al. [154] reported that the major essential oils constituents of Moroccan Labiatae *Origanum compactum* and *Thymus glandulosus* consisted of carvacrol, linalyl acetate and thymol. Both oils inhibited completely the growth of the mycelium of *Botrytis cinerea* at 100 ppm.

Serrano et al. [155] reduced the growth of yeasts and molds for stored cherries by developing active packaging materials containing eugenol, menthol, thymol and eucalyptol.

The essential oil of cinnamon had a high antifungal effect (very low minimum inhibitory concentration) against *Aspergillus flavus* [156, 157]. The antimycotic activity of *Cinnamomum zeylanicum* bark essential oil is due to the presence of cinnamaldehyde [158].

Carvacrol, the major active ingredient, of oregano oil was found to cause complete inhibition of *Saccharomyces cerevisiae* growth at 0.01%. Its potency was 1500 times that of the oregano oil. In contrast, the γ -terpinene, which is the biosynthetic precursor of carvacrol, was ineffective as a fungicide. Carvacrol interfered in the target of rapamycin signaling pathway, resulting in loss of viability. Eugenol, thymol and carvacrol affect Ca^{2+} and H^{+} homeostasis leading to loss of ions and inhibition of *Saccharomyces cerevisiae* [159]. Citral, citronellol, geraniol and geranyl acetate that are the major components of eucalyptus oil, tea tree oil and geranium oil possess cell cycle inhibitory activities against *Candida albicans* [160].

Sourmaghi et al. [161] found that hydrodistilled coriander essential oil had a potent antifungal activity against *Candida albicans*. Linalool was the major component in coriander oil. The essential oil of coriander had synergistic antimicrobial effect with amphotericin B [162].

Rahman et al. [153] reported that the hydrodistilled essential oil of the leaves of *Piper chaba* Hunter displayed potent antifungal activity against *Fusarium oxysporum*, *Phytophthora capsici*, *Colletotrichum capsici*, *Fusarium solani*, and *Rhizoctonia solani*. They attributed this activity to α -humulene, caryophyllene oxide, viridiflorol, globulol, β -selinene, spathulenol, (E)-nerolidol, linalool, 3-pentanol and *p*-cymene that present in the oil. At a concentration of 125 $\mu\text{g/mL}$, the fungicidal action of oil showed complete spore germination inhibition of *Phytophthora capsici*.

de Oliveira et al. [163] found that the essential oil of *Piper ilheusense* was active in combating activity of *Candida albicans*, *Candida krusei*, and *Candida parapsilosis*. (E)-Caryophyllene

and patchouli alcohol were the major components of the oil. γ -Cadinene, germacrene B and gleenol were found in significant quantities. Marino et al. [164] reported that the minor components might be involved in some type of synergism with the other active compounds.

4.4. Anticancer activity

Cancer is a multifactorial disease contributing towards the uncontrolled growth of the abnormal cells, leading to the formation of a tumor [165]. Carcinogenesis is a multistep process and oxidative damage that is linked to the formation of tumors. Secondary metabolites from different plants are capable of halting development of cancer [166]. Essential oil constituents have cytotoxic and antitumor activities. They play an important role in cancer prevention and treatment [18, 167]. Essential oils can be used in combination with cancer therapy to decrease the side effects of the drugs [168]. Cytotoxicity of essential oils is due to its action upon cellular integrity, leading to necrosis and apoptosis, cell cycle arrest and loss of key organelles function [169, 170]. Therefore, the evaluation of the anticancer activity of essential oils and their safety on normal cell lines are of great importance [171].

The essential oil of *Ricinus communis* leaves exhibited a moderate antiproliferative activity against cervical cancer line. The composition of the oil was predominantly by α -thujone and 1,8-cineole [172]. The *Eugenia caryophyllata* essential oil showed significant cytotoxic effects against HT29, A549 and Hep2 cancer cell lines. The cytotoxicity is likely due to the high concentrations of phenolic compounds, particularly eugenol [173].

Eugenol displayed cytotoxic action in a dose-dependent manner against human hepatoma cells HepG2 and colon cells Caco-2 [174], HL-60 leukemia cells [175] and osteoblastic cell line U2OS [176].

Terpenoids of essential oils prevent tumor cell proliferation [34]. Linalool and linalyl acetate represented the major constituents in lavender essential oil. They were more cytotoxic than the whole essential oil against 153BR, HNDF and HMEC-1 cancer cell lines [177]. Geraniol suppressed the growth of MCF-7 breast cancer cells [178] and PC-3 prostate cancer cells [179]. It was reported to interfere with membrane functions, ion homeostasis; inhibit DNA synthesis; and reduce the size of colon tumors [180]. β -Caryophyllene did not inhibit cell growth of MCF-7 breast cancer cell lines, but α -humulene was cytotoxic. However, β -caryophyllene potentiated the cytotoxicity of α -humulene [181]. Limonene and linalyl acetate had no effect on neuroblastoma cells. However, their combination induced apoptosis [182]. This synergic effect was consistent in several studies for antitumor properties [183].

Carvacrol is a major component of oregano and thyme essential oils. It inhibits tumor cell proliferation and induces apoptosis in human colon cancer cell lines, HCT116 and LoVo [184] and in human oral squamous cell carcinoma [185]. Perillyl alcohol decreases the growth of HCT116 cells [186].

5. Conclusion

The essential oils are multi-component systems, while their key components represent single component systems. Quality assurance of essential oils is imperative to ensure authenticity and product quality. The ratio of one special component or group of components to another is one of the quality indices of an essential oil as it affects its aroma.

Some of the essential oil constituents contribute to the essential oil antioxidant, antimicrobial and anticancer activities, regardless their concentration. They contribute by their synergistic effect to the property of the essential oil.

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